A METHOD FOR FORMING A POLARIZATION-INVERSED PORTION

Background of the Invention

[0001]

Field of the Invention:

This invention relates to a method for forming a polarization-inversed portion such as a periodical polarization-inversed structure usable for a second harmonic wave-generation (SHG) device utilizing a Quasi-Phase-Matching (QPM) system.

[0002]

Related Art Statement:

As a blue laser-light source usable for an optical pickup, etc., a SHG device utilizing a QPM system, having an optical waveguide constructed from a periodical polarization-inversed portion in a substrate made of a ferroelectric single crystal such as a lithium-niobate single crystal or a lithium tantalate single crystal, is expected. The device may be widely used for optical disk memory, medicine, optochemical field, and various optical measurement.

[0003] In order to realize a high conversion efficiency in the SHG device, it is required that the above polarization-inversed portion is formed deeply in the ferroelectric single crystal substrate. The deeply forming method of the polarization-inversed portion is, for example, disclosed in the Kokai publication Kokai Hei 9-218431 (JP A 9-218431). In the publication, a conventional voltage applying method is improved, and attempt is made to grow a polarization-inversed portion deeply from a main surface of a ferroelectric single crystal substrate by sloping the main surface thereof from the polarization axis thereof by 3 degrees.

[0004] Moreover, in the Kokai publication Kokai Hei 11-72809 (JP A 11-72809), a main surface of a ferroelectric single crystal substrate is inclined from a polarization axis of the ferroelectric single crystal substrate by 3 degrees,

and a ctenoid electrode and a virgate electrode are formed on the main surface, and several low electric resistance portions are formed in between the forefronts of the ctenoid electrode and the virgate electrode. Then, when a direct current is applied between the ctenoid electrode and the virgate electrode, polarization-inversed portions are formed corresponding to the electrode pieces of the ctenoid electrode and the low electric resistance portions.

[0005] As mentioned above, the forming method of the polarization-inversed portion described in the Kokai publication Kokai Hei 11-72809 can certainly form the polarization-inversed portions corresponding to the electrode pieces of the ctenoid electrode and the low electric resistance portions. However, since a given space is placed in between the forefronts of the electrode pieces of the ctenoid electrode and the low electric resistance portions and in between the adjacent low electric resistance portions, the above polarization-inversed portions have given spaces therebetween. That is, the polarization-inversed portions are formed in separation. If a ferroelectric single crystal substrate having the above-mentioned periodical polarization-inversed portion is employed for a SHG device utilizing a QPM system, a fundamental wave interacts with only the forward polarization-inversed portions, that is, the polarization-inversed portions corresponding to the electrode pieces of the ctenoid electrode. Therefore, the conversion efficiency for a second harmonic wave may not enhanced.

Summary of the Invention

[0006] It is an object of the present invention to provide a new method for forming a polarization-inversed portion deeply from a main surface of a ferroelectric single crystal substrate having a single polarized domain.

[0007] This invention relates to a method for forming a polarization-inversed portion comprising the steps of:

preparing a substrate made of a ferroelectric single crystal,

fabricating a first electrode and a second electrode on a main surface of the substrate in separation,

applying a first voltage to between the first electrode and the second electrode to generate and grow a first polarization-inversed portion toward the

5   second electrode from the first electrode,

changing the distance between the first electrode and the second electrode, and

applying a second voltage to between the first electrode and the second electrode to generate and grow a second polarization-inversed portion, in a

10   different area from that of the first polarization-inversed portion, toward the second electrode from the first electrode.

[0008]   The inventors have conceived that after some polarization-inversed portions (first polarization-inversed portions) are formed by a voltage applying method using a first electrode and a second electrode, additional polarization-

15   inversed portions (second polarization-inversed portions) are formed in the different area by changing the distance of between the first electrode and the second electrode.   The first polarization-inversed portion and the second polarization-inversed portion have their respective different depth for a main surface of a ferroelectric single crystal substrate.   Therefore, if the distance

20   between the first electrode and the second electrode is adjusted appropriately, the overlapping degree of the first polarization-inversed portion and the second polarization-inversed portion can be controlled.   A conventional forming method of a polarization-inversed portion as described in the Kokai publication Kokai Hei 11-72809 can not control the overlapping degree of the polarization-

25   inversed portions.

[0009]   Herein, the "voltage applying method" means a method that a first electrode and a second electrode are provided on a main surface of a ferro-electric single crystal substrate so as to be opposed each other, and a given

voltage is applied between the first electrode and the second electrode on the condition that the first electrode is positive, thereby to grow a polarization-inversed portion along the polarization axis from the first electrode. The voltage applying method is explained in the Kokai publications Kokai Hei 9-218431 and

5   Kokai Hei 11-72809.

[0010]   In a preferred embodiment of the present invention, the first electrode is constructed from a ctenoid electrode having plural strip electrode pieces, and the distance between the first electrode and the second electrode is changed by adjusting the lengths of the electrode pieces after the first polarization-inversed

10   portion. In this case, a desired periodical polarization-inversed structure can be formed easily.

[0011]   The distance between the first electrode and the second electrode can be increased or decreased. In the case of increasing the distance, it is desired that a part of at least one of the first electrode and the second electrode is

15   removed by etching treatment or dicer processing after the first polarization-inversed portion. Or another first electrode or another second electrode may be formed, by conventional photolithography technique, on the main surface of the ferroelectric single crystal substrate after the above first electrode or the above second electrode is removed entirely.

20   [0012]   Particularly, in light of the number of the processing steps for the ferroelectric single crystal substrate, the former distance-increasing method is preferable because it requires not so many processing steps. In the case of using the ctenoid electrode as the first electrode, the distance between the first electrode and the second electrode can be easily increased by shortening the

25   electrode pieces of the ctenoid electrode through etching treatment or dicer processing.

[0013]   In the case of forming the second polarization-inversed portion on the condition that the distance between the first electrode and the second electrode is

increased, the electric potential of the first electrode may be set to be almost equal to that of the first electrode in the case of forming the first polarization-inversed portion. However, in this case, the second polarization-inversed portion is likely to be formed small due to the increased distance between the first electrode and the second electrode. Therefore, in order to develop the size of the first polarization-inversed portion, the electric potential of the first electrode in forming the second polarization-inversed portion is set to be larger than that of the first electrode in forming the first polarization-inversed portion.

[0014] In the case of forming the second polarization-inversed portion on the condition that the distance between the first electrode and the second electrode is decreased, the electric potential of the first electrode can be also set to be almost equal to that of the first electrode in the case of forming the first polarization-inversed portion. However, in this case, the second polarization-inversed portion is likely to be large due to the decreased distance between the first electrode and the second electrode. Therefore, in order to reduce the size of the second polarization-inversed portion, the electric potential of the first electrode in forming the second polarization-inversed portion is set to be smaller than that of the first electrode in forming the first polarization-inversed portion.

[0015] As mentioned above, the size of the first polarization-inversed portion or the second polarization-inversed portion can be controlled by adjusting the voltage between the first electrode and the second electrode even though the distance between the first electrode and the second electrode is changed.

Brief Description of the Drawings

For a better understanding of this invention, reference is made to the attached drawings, wherein:

Fig. 1 is a schematic view showing an arrangement of a ferroelectric single crystal substrate, a first electrode, a second electrode and a planer electrode in the case of forming a first polarization-inversed portion,

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Fig. 2 is a schematic view showing an arrangement of a ferroelectric single crystal substrate, a first electrode, a second electrode and a planer electrode in the case of forming a second polarization-inversed portion,

Fig 3a is a plan view showing an arrangement of the first electrode and the second electrode in the case of forming the first polarization-inversed portion,

Fig 3b is a cross sectional view taken on line IIIb-IIIb of the ferroelectric single crystal substrate schematically showing the first polarization-inversed portion,

Fig. 4a is a plan view showing an arrangement of the first electrode and the second electrode in the case of forming the second polarization-inversed portion,

Fig. 4b is a cross sectional view taken on line IVb-IVb of the ferroelectric single crystal substrate schematically showing the first polarization-inversed portion and the second polarization-inversed portion,

Fig. 5 is cross sectional view schematically showing the first polarization-inversed portion and another second polarization-inversed portion,

Fig. 6 is a photograph showing a first polarization-inversed portion and a second polarization-inversed portion in a ferroelectric single crystal substrate, and

Fig. 7 is a photograph showing a first polarization-inversed portion and a second polarization-inversed portion in a ferroelectric single crystal substrate.

Detailed Description of Preferred Embodiments

[0016] This invention is described in detail hereinafter, with reference to the attached drawings.

Fig. 1 is a perspective view schematically showing an arrangement of the ferroelectric single crystal substrate, the first electrode, the second electrode and the planer electrode in forming the first polarization-inversed portion, and

Fig. 2 is a perspective view schematically showing an arrangement of the ferroelectric single crystal substrate, the first electrode, the second electrode and the planer electrode in forming the second polarization-inversed portion.

[0017] A first electrode 2 and a second electrode 4 are provided on a main surface 1a of a substantially rectangular parallelepiped substrate 1 made of a ferroelectric single crystal. The first electrode 2 has a strip virgate portion and plural strip electrode pieces 3A elongating toward the second electrode 4.

A planer electrode 5 is provided on the rear main surface 1b of the substrate 1. The ferroelectric single crystal constituting the substrate 1 has a polarization axis parallel to a Z-axis, and the substrate 1 is sloped for the Z-axis by an angle θ. Then, an electric power supply 6 is provided between the first electrode 2 and the second electrode 4, and an electric power supply 7 is provided between the first electrode 2 and the planer electrode 5.

[0018] In this case, the distance between the forefronts of the electrode pieces 3A of the first electrode 2 and the second electrode 4 is set to LA as shown in Fig. 3a. When a given voltage is applied between the first electrode and the second electrodes from the electric power supply 6 and/or 7, polarization-inversed portions are generated and grown toward the second electrode 4 from the forefronts of the electrode pieces 3A of the first electrode 2. As a result, for example, a first polarization-inversed portion 10A is formed under the second electrode 4 as shown in Fig. 3b.

[0019] Subsequently, as shown in Figs. 2 and 4a, the forefronts of the electrode pieces 3A are removed and shortened, and the distance between the forefronts of the electrode pieces 3B of the first electrode 2 and the second electrode 4 is set to LB larger than the distance LA. When a given voltage is applied between the first electrode 2 and the second electrode 4 from the electric power supply 6 and/or 6, polarization-inversed portions are generated and grown toward the second electrode 4 from the forefronts of the shortened electrode

pieces 3B of the first electrode 2. As a result, for example, a second polarization-inversed portion 10B is formed under the second electrode 4 as shown in Fig. 4b.

[0020] In this case, if almost the same voltage is given to between the first electrode and the second electrode in forming the first polarization-inversed portion and the second polarization-inversed portion, the size of the second polarization-inversed portion is likely to be smaller than that of the first polarization-inversed portion. If a voltage to be applied to between the first electrode and the second electrode in forming the second polarization-inversed portion is set to be larger than that in forming the first polarization-inversed portion, the second polarization-inversed portion may have a size almost equal to or larger than that of the first polarization-inversed portion.

[0021] The given voltage to be applied to between the first electrode and the second electrode is normally set to 1.5-5.0 kV. In the case of using a different voltage in forming the second polarization-inversed portion, the voltage ratio is preferably set to 1.1 times or over.

[0022] Moreover, the pulse frequency of the voltage to be applied to between the first electrode and the second electrode may be changed. In this case, the difference in pulse frequencies in forming the first polarization-inversed portion and the second polarization-inversed portion is preferably set to 10% or over.

[0023] Moreover, the distance ratio (LB/LA) is preferably set to 1.25 or below. Thereby, the first polarization-inversed portion and the second polarization-inversed portion are easily combined each other. Then, the distance ratio (LB/LA) is preferably set to 1.05 or over.

[0024] Then, for example, another first electrode may be fabricated after the first electrode 2 may be removed, thereby to set the distance LA to be larger than distance LB. In this case, the distance ratio (LA/LB) is preferably set to within 1.05-1.25.

[0025] In the case that the distance LB is set to be larger than the distance LA using, as the first electrode, the ctenoid electrode having the removed electrode pieces as shown in Figs. 2 and 4a, the length MA of the electrode pieces 3A of the ctenoid electrode is larger than the length MB of the removed electrode pieces 3B of the ctenoid electrode. The length ratio (MB/MA) is preferably set to 0.7 or over. Thereby, the first polarization-inversed portion and the second polarization-inversed portion can be easily combined. Moreover, in order to effectively and easily form the second polarization-inversed portion in a different position from that of the first polarization-inversed portion, the length ratio (MB/MA) is preferably set to 0.9 or over.

[0026] In the case that the distance LB is set to be smaller than the distance LA, for example using the another first ctenoid electrode having the longer electrode pieces as mentioned above, the length MA of the electrode pieces 3A of the ctenoid electrode is smaller than the length MB of the removed electrode pieces 3B of the ctenoid electrode. The length ratio (MA/MB) is preferably set to within 0.7-0.9.

[0027] If the above process is repeated, many polarization-inversed portions such as a third polarization-inversed portion and a fourth polarization-inversed portion can be made.

[0028] In this invention, the substrate 1 may be made of a ferroelectric single crystal such as lithium niobate ($LiNbO_3$), lithium tantalate ($LiTaO_3$), potassium lithium tantalate ($K_3Li_2Nb_5O_{15}$), lithium niobate-lithium tantalate ($LiNb_{1-x}Ta_xO_3$ ($0<X<1$)) or the like. Particularly, the substrate 1 may be preferably made of lithium niobate, lithium tantalate or lithium niobate-lithium tantalate because they have their well known polarization-inversed properties.

[0029] In order to develop optical damage-resistance of the substrate, the above ferroelectric single crystal may incorporate at least one element selected from the group consisting of magnesium (Mg), zinc (Zn), scandium (Sc), indium

(In) or at least one oxide of the respective oxides of the above mentioned metal elements. Moreover, the ferroelectric single crystal may incorporate at least one element from a lanthanide series such as neodymium (Nd), erbium (Er), thulium (Tm), holmium (Ho), dysprosium (Dy), praseodymium (Pr).

5   **[0030]**   The substrate 1 may have any shape, but preferably have a planer shape.

[0031]   It is not required that the main surface 1a of the substrate 1 is inclined for the polarization axis thereof, but may be inclined by 0.2-80 degrees, particularly 0.2-45 degrees.   In fabricating a SHG device using QPM system from the substrate, the inclination angle θ is preferably set to within

10   0.2-10 degrees.   As a result, a second harmonic wave having a TE mode polarization can travel into the SHG device easily.

[0032]   Moreover, the above given voltage may be applied to between the first electrode 2 and second electrode 4 from the electric power supply 6 on condition that the second electrode 4 is negative.   Moreover, the above given

15   voltage may be applied to between the first electrode 2 and the second electrode 4 on condition that the planer electrode 5 is negative.   Then, the above given voltage may be applied to between the first electrode 2 and the second electrode 4 on condition that the second electrode 4 and the planer electrode 5 are negative.

[0033]

20   Examples:

(Example 1)

Following the above process as shown in Figs. 1-4, the first polarization-inversed portion 10A and the second polarization-inversed portion 10B were formed.   Concretely, the substrate 1 was fabricated in a size of 3 inch

25   diameter × 1.0 mm thickness from 5 atomic % Mg doped lithium niobate single crystal.   Then, the electrodes 2, 4 and 5 were fabricated of Ta by a photo-lithography method.   The pitch of the electrode pieces 3A was set to 3 μm for generating a SHG light having a wavelength around 400 nm.   The length MA

of the electrode pieces 3A was set to 100 µm. The distance LA between the electrode pieces 3A of the first electrode 2 and the second electrode 4 was set to 400 µm.

[0034] A pulsed voltage of 4.0 kV with a pulse width of 20 msec, a frequency of 25 Hz, a pulse number of 6 and a upper limit current value of 2 mA was applied to between the first electrode 2 and the second electrode 4 from the electric power supplies 6 and 7, to form a periodical polarization-inversed portion having a depth of 1.5 µm along the polarization axis of the substrate 1.

[0035] Thereafter, the forefronts of the electrode pieces 3A of the first electrode 2 were removed by etching treatment to form the removed electrode pieces 3B having a length of 75 µm. Next, the second polarization-inversed portion was formed as above.

[0036] The substrate 1 was cut off on a surface perpendicular to the polarizing direction of the substrate 1 (Z-direction) and was polished. The section of the substrate 1 was etched by a mixed solution of hydrofluoric acid and nitric acid, and was photographed as shown in Fig. 6. As is apparent from Fig. 6, the periodical polarization-inversed portion has a rectangular shape of a width of 1.9 µm and a depth of 2.2 µm.

[0037]

(Example 2)

Except that the length MB of the removed electrode pieces 3B of the first electrode 2 was set to 50 µm through etching treatment, the first polarization-inversed portion and the second polarization-inversed portion were formed by the same manner as in Example 1. The substrate 1 was cut off, etched and photographed as shown in Fig. 7, as in Example 1, in order to investigate the condition of the thus obtained periodical polarization-inversed portion.

As is apparent from Fig. 7, the first polarization-inversed portion and the second polarization-inversed portion were formed in separation, the second

polarization-inversed portion was formed in a deeper area in the substrate 1.

[0038]   Although the present invention was described in detail with reference to the above examples, this invention is not limited to the above disclosure and every kind of variation and modification may be made without departing from the scope of the present invention.

[0039]   As mentioned above, a new method for forming a polarization-inversed portion deeply from a main surface of a ferroelectric single crystal substrate having a single polarized domain can be provided.